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Applying Digital Virtual Restoration and Three-dimensional Sand-Printing for Missing Parts of Rampart Walls

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Abstract

A rampart had been relatively severely damaged owing to weathering, and some of the rampart stones were missing because of soiling, resulting in structural and esthetic damages. In this study, digital virtual restoration and sand-printing techniques were used to improve the stability of the rampart and its viewing environments. First, a virtual restoration of weathered stones reflecting the surface texture with a handheld precision scanning and haptic modeling system was conducted and a simulation wherein a metal support was added to examine the field applicability of the finished 3D model was performed. The restored rampart stones were printed with settings of lamination thickness of 0.28 mm out of the sand of an average of 140μm. The printed rampart stones received a finishing touch with reinforcing treatment after separating and drying processes. To apply the printed stones, metal supports were placed in accordance with the virtual simulation results, and the rampart stones were installed in the missing parts. In the restoration process, no structural problems were encountered, such as gaps or falling, and the inserted stones well demonstrated the features of the existing weathered stones, fitting in the surrounding stones with little obvious dissimilarities. This study showed significant implications for transforming traditional restoration methods into a contactless digital method. Further, it expanded the variety of printing materials using sand that best resembles the rampart wall within 3D printing materials that are the most similar to those of the rampart. If the durability and stability of the sand printed materials are fully verified in the future, they could be widely used in restoring outdoor buildings and stone cultural heritage.

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1. Introduction

Restoration of damaged cultural heritage is commonly conducted with manual methods based mainly on the experience and techniques of skilled experts. Moreover, restoration principles pursue reversibility, but its practical application is limited and in some cases, secondary damage can occur owing to improper restoration. However, with the recent rapid development of digital technology, new approaches have emerged in cultural heritage restoration methods. Representative technologies include three-dimensional (3D) scanning and printing.

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Because 3D scanning allows the current shape of cultural heritage to be digitalized in three dimensions, it is widely used in various fields such as production techniques, conservation management, and monitoring as well as documentation [1-3]. Furthermore, 3D printing is an advanced technology actively used at home and abroad to restore and replicate cultural heritage based on customized modeling data [4]. In particular, the convergence of these two technologies is essential for the conservation of cultural heritage and several success cases have been reported [5,6].

Notably, because there are many types of 3D printers, clearly establishing the application purpose is vital before selecting the output methods and materials. Previously reported 3D printing cases mainly involved the movable artifacts and are rarely used in outdoor cultural heritage buildings or historic sites. This appears to be related to material durability and output scale.

The rampart, the subject of this study, has been exposed to the natural environment for a long time and has undergone an overall high degree of weathering. It is severely weathered and has been decomposing into soil owing to granular disintegration as well as cracking, blistering, and exfoliation. Some rampart stones have been missing, thus compromising the esthetics and causing structural instability. Deconstruction restoration is mainly used to reinforce the missing parts of the rampart. However, this method can lead to excessive restoration, reduce the usability of old materials, and result in heterogeneity because of the insertion of new materials. Therefore, in this study, the structural stability of the rampart was strengthened with metal supports for the missing parts under the principle of maintenance and emergency conservation. Moreover, the 3D scanning and haptic modeling system virtually restored weathered stones reflecting the surface texture of the rampart, and their output using a 3D sand-printer facilitated esthetic restoration.

2. Methods

To improve the stability of the rampart and enhance the viewing environment, aesthetic restoration should be combined with structural reinforcement (Figure 1). Thus, this study is divided into five stages. First, 3D scanning was performed to digitize the missing parts of the rampart, and the scanned data of the stones around the missing parts was used as a reference to reflect the surface texture of weathered stones.

Furthermore, the virtual restoration of the rampart stones was conducted with a haptic modeling system. Using the simulation of the modeling results, challenges regarding on-site application in the field were identified in advance for better performance. 3D sand-printing using binder jetting for material similarity and durability was used to produce the output of digitally restored rampart stones. The finished rampart stones were installed on the missing parts with metal supports based on the results of the virtual simulation.

Figure 1. Digital restoration processes of damaged rampart walls.

3. Three-dimensional Scanning and Shape Analysis

3.1. Three-dimensional Scanning Results

3D scanning is divided into the 3D scan wherein the shape of a cultural heritage item is measured and transformed into structured point clouds and a data processing stage wherein a 3D structure is

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created using the point clouds [6]. The missing parts of the rampart walls in this study are located approximately 4 m above the ground, and the front wall is used as a parking space (Figure 2). Therefore, handheld precision scanners (Artec3D, Eva) with easy field accessibility were used to acquire 3D shape information of the missing parts of the rampart walls.

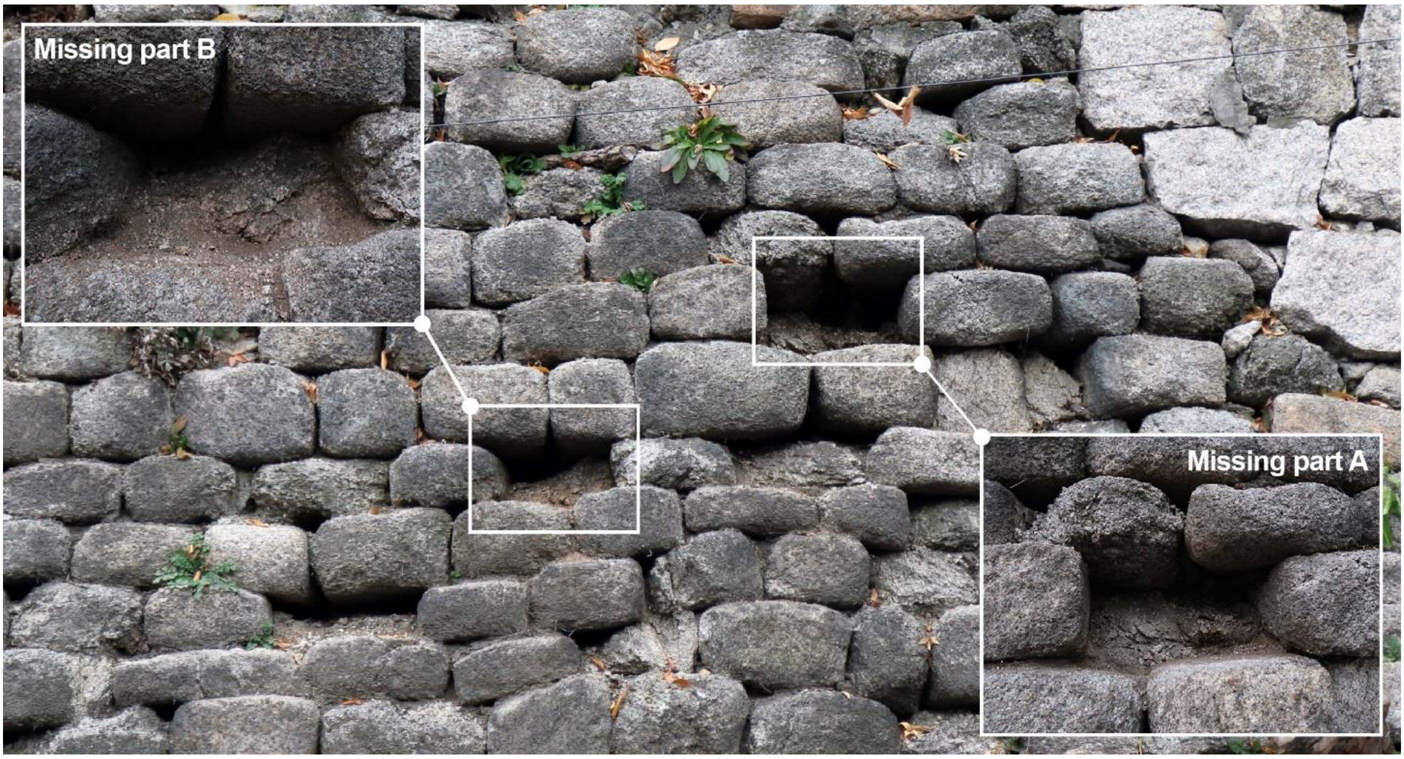

Figure 2. Occurrence and deterioration states of the rampart walls.

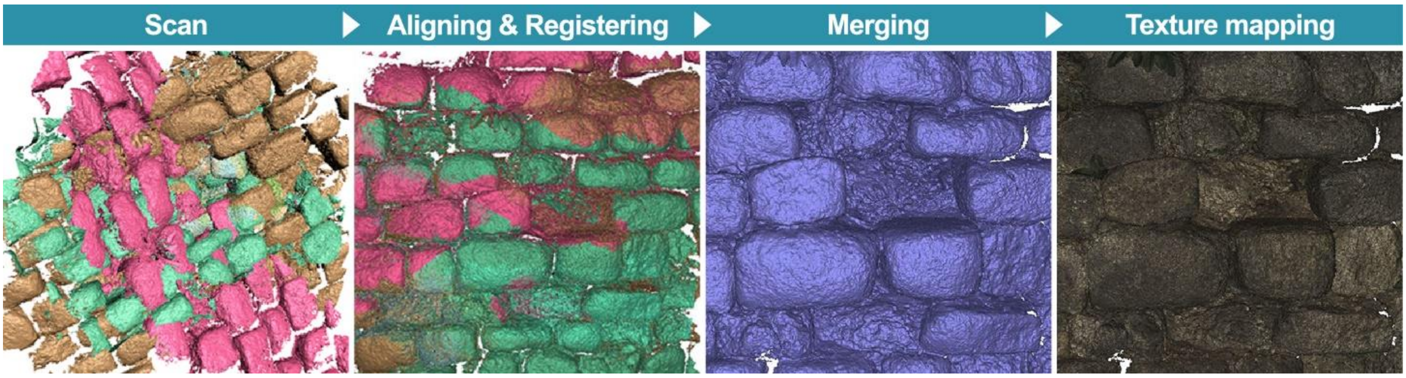

Figure 3. 3D scan data processing of the rampart walls.

Equipped with an LED flashlight bulb and a single lens camera (1.3 MP), this scanner acquires numerical data by triangulation using structured light. Moreover, it is widely used in various fields, such as precision industry, medicine, rapid prototyping, and digital documentation, because of its high accuracy, fast data acquisition speed, intuitive processing method, and lightweight structure. Its average data accuracy is 0.5 mm per meter and it supports 24 bpp RGB color. On-site scans were immediately conducted after sunset to prevent structural light interference by direct sunlight and to form a 3D structure of missing parts of the rampart and weathered stone surface texture.

The scanned data acquired in the field was modeled after filtering, aligning, registering,

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merging, and RGB color mapping (Figure 3). First, the noise was removed from each frame and then ICP algorithm-based alignment was performed. The data then went through continuous aligning to rearrange the frames, fine aligning to position the connected frames between the same structures, global registering to bind the structures into one coordinate system, and merging to generate combined structure data. Finally, RGB color was mapped to the polygon model of the rampart walls to complete a 3D scanning-based rampart model.

3.2. Shape Analysis Results

The results of analyzing the shape of the rampart walls via the 3D scanning model show that missing parts inclined inward by approximately 9°. Further, the cross-section analysis of the internal shape of the rampart walls showed that both missing parts A and B have deeper depths in the upper part than in the lower part, implying that the minor axis of the lower part of the missing parts should be the criterion for determining the thickness of each stone model during digital virtual restoration (Figure 4).

Moreover, depth modeling was conducted to understand the surface texture of 3D scanned weathered stones. This method is among the widely used approaches in visualizing heritage and assessing the conservation state. As a result, weathered stones were used to express the surface texture of the stone during virtual restoration and as a reference to the edge structure (Figure 5).

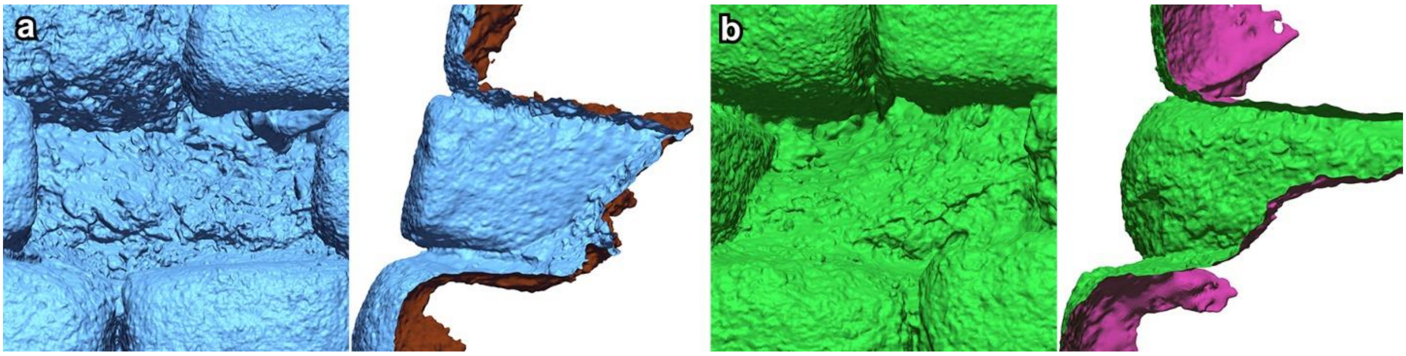

Figure 4. Detailed 3D shape of damaged rampart walls. (a) Missing part A. (b) Missing part B.

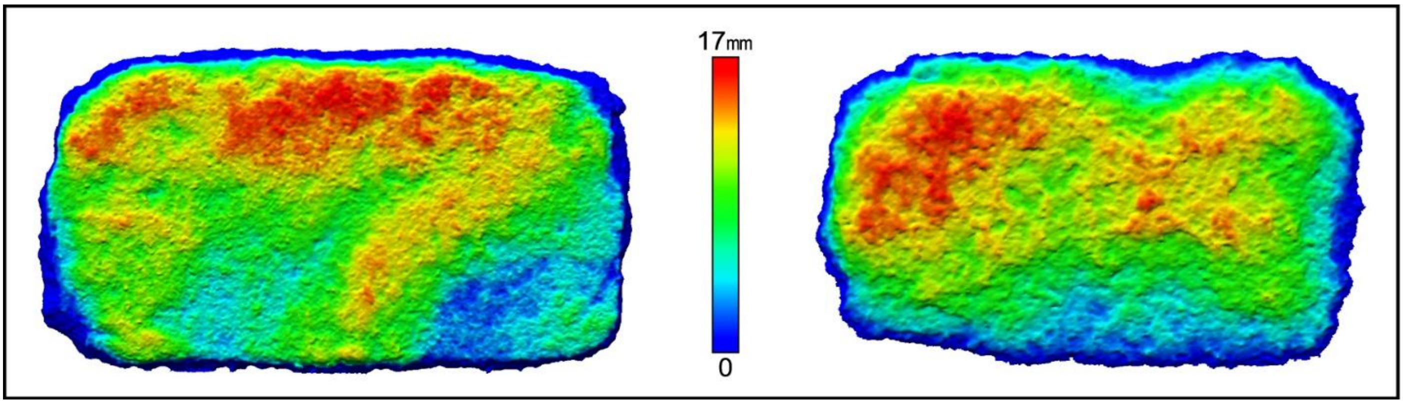

Figure 5. Depth modeling results of 3D scanned weathered stones.

4. Virtual Restoration Modeling

4.1. Virtual Restoration Principles

The rampart walls used herein have been damaged owing to various factors, including physical damage such as granular disintegration and soiling, structural deformation caused by stone loss, and chemical weathering because of blackening contaminants. In particular, for the missing parts, because there is no data on the original stone, it is important to minimize the subjective intervention and ensure objectivity when modeling virtual restoration. However, the stones around the missing parts were similarly sized and weathered, allowing them to be used as a reference model for esthetic restoration.

The rampart itself is a structure with individual stones whose function is also important. As the missing parts cannot support the load above, it may impose an unbalanced load onto the surrounding stones, which eventually leads to structural instability if it persists. Therefore, this study employed virtual restoration modeling, in which metal supports and 3D printing output can be installed together to facilitate structural reinforcement. This principle was constantly reflected in the modeling process, thus providing an important contribution in improving the finished virtual stones.

4.2. Modeling and Assembly Simulation

The virtual restoration of missing parts was performed using 3D haptic modeling system (3D Systems, TouchX device and FreeForm Plus software). This system enables intuitive modeling, where the data in the digital virtual space is used as a haptic device and can generate and modify structures based on voxel units. It is now widely used in medical fields, forensics, cultural heritage, and interactive contents [7-10].

For virtual restoration modeling of the rampart walls, data optimization was conducted so that 3D precision scanning data can be represented by high resolution voxels (0.1 mm). Then, a base axis of the walls was established, and the overall shape of the rampart stones was created by the Boolean operation using virtual clay. In addition, weathering texture on the surface was expressed through reference data of surrounding rampart stones. Final 3D model of the rampart stones was completed subsequent to supplementing contacting parts between the virtually restored rampart stones and walls (Figure 6).

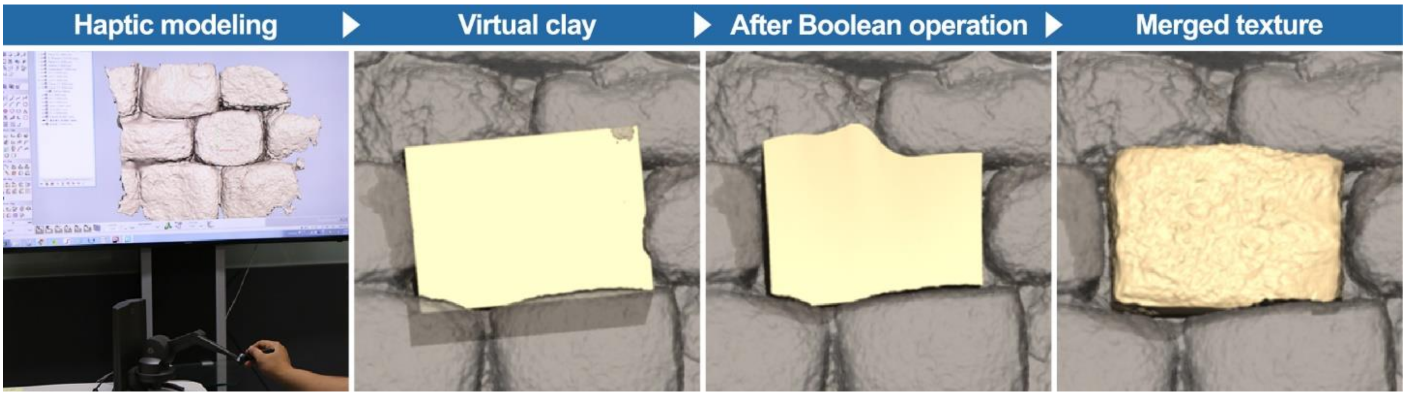

Figure 6. 3D modeling processes of missed rampart stone.

Virtual assembly simulation was conducted to verify the field applicability of the restored rampart stone. The most important consideration for the virtual assembly of rampart stone is the positioning of the metal supporter that is used to facilitate structural reinforcement. Therefore, subsequent to establishing the installation location of the metal supports inside the missing parts, the space was secured by partially removing the rampart stone. The simulation examined the location of the virtual restoration stones and connection with the metal supports through cross sections and projections and adjusted the insertion depth by considering the slope of the rampart walls to avoid an inversion of the stones (Figure 7). The virtual simulation has made a significant contribution to prevent secondary damage and enhance the field applicability for the restoration of parts.

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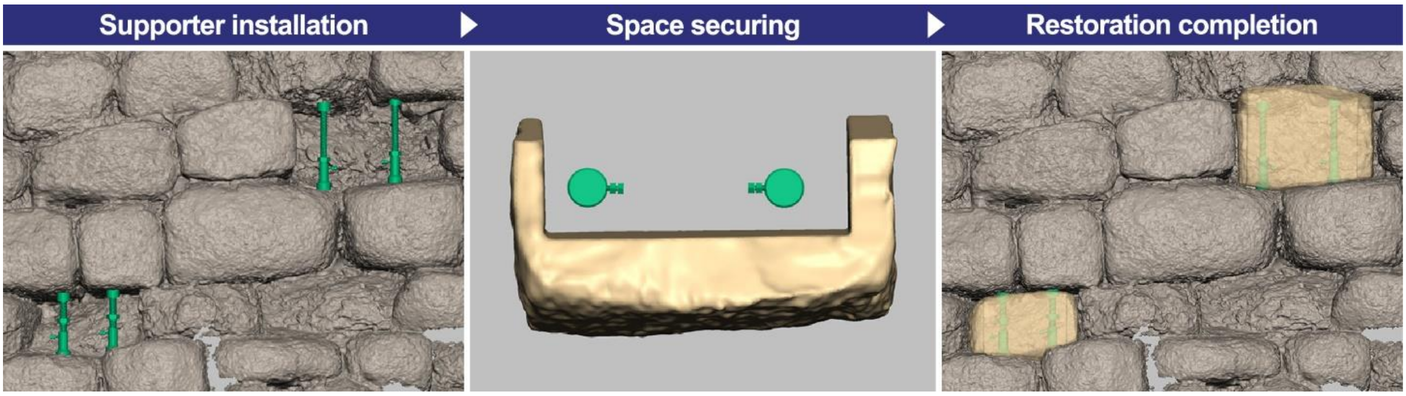

Figure 7. Virtual assembly simulation processes for the field applicability of the restored rampart stones.

5. Three-dimensional Sand-printing and Field Application

3D printing is a technology in which 3D models fabricated using computer graphics or scanning are differentiated into 2D cross sections, reconstruction is sequentially performed, and then the materials are laminated layer by layer to form a structure. 3D printing methods are classified by many institutions and researchers based on the formative principles and materials [11-13], and the most widely used among them is the classification method by the American Society for Testing and Materials (ASTM). Major 3D printing technologies defined in ASTM F2792-12a are largely based on seven criteria. These standards have also been adopted by the international standard ISO TC261.

In this study, binder jetting was selected to print 3D virtual restoration results of missing parts of the rampart walls. The output material was sand with a size of approximately 140 μm and layer thickness of 0.28 mm. The first result emerged after approximately two days of printing after the virtual restoration model was loaded in the printing software (Figure 8a). The sand was then shaken with an air gun, and the adhesive used for lamination was sufficiently dried at room temperature (Figure 8b). The additional hardening treatment to enhance the strength of the output led to the completion of the final rampart stones (Figure 8c).

Figure 8. 3D sand-printing of the rampart stone for field application. (a) Virtual restoration model for 3D printing. Prior (b) and subsequent to (c) the hardening treatment of 3D sand-printing output.

For the on-site application of the 3D sand printed stones, metal supports were placed based on the virtual simulation results and printed stones were installed in the missing parts. In this process, no structural problems such as gaps or fallings were encountered. The stones were installed as planned,

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indicating that the virtual simulation was successful (Figure 9). The restored stones of the rampart walls well represented the existing weathered stones surface, demonstrating little heterogeneity with the surrounding original rampart stones.

Figure 9. Restoration of damaged rampart walls using metal supporters and 3D sand-printing outputs.

6. Discussion and Conclusion

In principle, original materials and traditional techniques are used to restore missing parts of the rampart walls. However, currently, the supply and demand of original materials are challenging, and it is nearly impossible to apply traditional techniques to all restorations. In consequence, various restoration methods are applied and discussed as the next best solution. 3D printing technology is also not an ideal way to restore cultural heritage, but it has the advantage of providing customized non-contact production compared to other methods. It is also an optimal method for cases such as the rampart in this study in which esthetic restoration was considered along with structural functions.

In this study, 3D scanning and printing technologies were applied to the restoration of missing parts of the rampart and esthetic restoration was enhanced by reflecting the surface texture of the weathered stones. In particular, the rampart stone output by binder jetting using sand enhances the visual stability for the visitors and metal supports reinforce the structural functions. Simulations using the virtual restoration model enabled us to check all possible problems in advance related to on-site application. Furthermore, this study proposed a new restoration method in which the contact method used for the restoration of the rampart is switched to contactless digital restoration based on the 3D scanning, virtual restoration, and printing technologies.

It is expected that additional restoration can be easily accomplished using the original data already obtained in this study even if parts of the rampart are lost in the future. However, in previous studies, there have been few cases in which 3D sand-printing technology has been applied to the restoration of outdoor cultural heritage. Thus, it is essential to have material properties and shape deformation monitored. In particular, it seems necessary to fully verify material durability and stability through various experimental studies and produce methods for improving the materials and expanding the application.

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